

Effect of Taphonomic Processes on Dental Microwear

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ABSTRACT Taphonomic processes have the potential to affect microscopic wear on teeth and to modify the wear patterns so as to confound dietary reconstructions based on dental microwear which was formed during the lifetime of an animal. This study describes a series of experiments which were conducted to simulate various taphonomic agents and to record their effect on dental microwear. Three types of experiment were carried out in order to explain anomalous microscopic wear that had been found on the dentition of several hominoid specimens from the 15 M.a. site of Paşalar in Turkey. The effect of two different acids—citric and hydrochloric acid—on dental microwear was investigated. Modification to microscopic wear caused by alkali (carbonate ash) was examined in the second set of experiments. Lastly, the effect of abrasion by three different size classes of sediment from the site of Paşalar—quartz pebbles (grain size varied from 2,000–11,000 μm), coarse sand (grain size ranged from 500–1,000 μm), and medium-sized sand (grain diameters were between 250 and 500 μm)—was investigated. Results confirm previous findings that the taphonomic modification of dental microwear is readily identifiable and causes the obliteration rather than secondary alteration of microwear features. The experiments show that both citric and hydrochloric acid affect dental microwear but to varying degrees, whereas alkali did not cause any modification of microscopic features. The different size classes of sediment also had different effects on the dental microwear. The largest size sediment (quartz pebbles) polished the enamel and removed finer microwear features. The coarse sand, however, did not have any effect on the microwear. The greatest amount of abrasion was caused by the smallest sediment particles—the medium-sized sand. Several hominoid dental specimens from Paşalar display similar microscopic wear to the two types of acid erosion and the abrasion caused by the medium-sized sands. *Am J Phys Anthropol* 108:359–373, 1999. © 1999 Wiley-Liss, Inc.

During an animal's lifetime, microscopic alterations to its teeth reflect the diet it ingests. The examination of these wear marks (dental microwear) has been an important tool in the reconstruction of palaeodiet for more than 20 years (for reviews see Gordon, 1988; Teaford 1988, 1991, 1994). However, after death a number of agents have the potential to cause damage to the

enamel that is not related to the ingestion of food. Taphonomic processes are those which

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affect the bones of an animal after its death through to fossilisation and recovery and conservation of the remains. Sedimentary abrasion, weathering, and exposure to an acidic environment are just a few of the taphonomic agents that have the potential to alter or obliterate existing microscopic features, and they need to be taken into consideration by researchers making dietary inferences based on dental microwear analysis. In addition, specimens may be damaged during and after recovery. For example, cleaning can often affect enamel, but these types of postmortem damage are not under investigation here.

Several experiments have been done to simulate taphonomic processes and to document their effects on enamel and dental microwear features (e.g., Gordon, 1983, 1984; Puech et al., 1985). In an investigation of the effects of sedimentary transport on microwear, Gordon (1983 and 1984) tumbled human teeth in four different types of dry sediment and in aqueous mixtures of these sediments. She found that microwear features were altered and in some circumstances completely obliterated, with the amount of alteration to the microwear being positively correlated with the size of the sediment particles. There was no evidence, however, that new features were added to existing microwear patterns. Puech et al. (1985) also conducted an experiment in which a tooth was abraded with an air-propelled stream of sand. At first the enamel became pitted, and then it took on a rough, eroded appearance, often with the abrasive damage following the orientation of the enamel prisms. Striations were formed when sand particles were rubbed across the enamel surface of another specimen. These authors observed that aprismatic enamel was eroded after a tooth was tumbled in water only and that the superficial enamel on another specimen was dissolved, with remaining features being blunted after tumbling in seawater. When quartz was added to the seawater, the tooth became rounded, and some pieces of enamel were chipped away from the surface. A number of striations were formed similar to those produced by the sand abrasion experiment. As the distance travelled by the tooth in the tumbler increased, the abrasion

process became more rapid (exponentially, as the speed of abrasion was not greatly accelerated until after 400 km of tumbling). The total distance that the specimen travelled was 4,000 km, although the time taken for this is not given the authors.

The effect of the chemical erosion of enamel was also investigated by Puech et al. (1985) who etched a tooth with a 30% solution of phosphoric acid for 60 sec. Initially shallow pits appeared in the enamel which, with repeated applications of acid, then enlarged to expose a network of enamel prisms. Eventually the prisms could no longer be distinguished, and no features could be seen at all.

THE SITE

The Miocene site of Paşalar is situated in northwestern Turkey 75 km southwest of the town of Bursa. German geologists discovered the site in 1969, and excavations were carried out in 1969 and 1970, during which 86 complete hominoid teeth were recovered (Andrews and Tobien, 1977). In 1983, systematic excavations were resumed at the site and continue to the present day (Alpagut, 1990).

The deposits at Paşalar form two distinct series—the lower series and the upper series—that are derived from two different sources. The lower series sediments contain two fossiliferous units. Four stratigraphic sections have been described: lower calcareous silt, fossiliferous sand, upper sand, and upper calcareous silt (Andrews and Alpagut, 1990). The fossiliferous sand is the main fossil-bearing unit and consists of poorly sorted sands, gravel, silt (Andrews and Alpagut, 1990). This unit consists of three levels: the upper level, which contains the lowest concentrations of fossils and consists of mainly fine sands; the middle section, which is comprised of gravelly, fine sand and contains large amounts of small mammals and a few larger ones; and the lower half, which consists of coarse sands and gravel and contains the greatest proportion of large mammals and hominoids (Andrews, 1995). The lower series sediments at Paşalar are locally derived.

Two stages of fossil accumulation and deposition have been described for the fossiliferous sands (Andrews, 1995). The first

phase involved the accumulation of the bones before burial. The evidence for this comes from the pattern of surface weathering which indicates slow accumulation of bones over a period of time (Andrews, 1995). The fossils were then transported with the sediments to the fossil site, and burial occurred rapidly, probably in a matter of days (Andrews and Alpagut, 1990) in a single depositional event. The fauna is thus restricted in temporal and geographic space.

Fifty-two mammalian species have been identified at Paşalar, and the assemblage is considered to be a natural community where many of the species were contemporaneous (Andrews, 1990, 1995). The hominoid specimens from Paşalar include three maxillae, two mandibles, 603 complete permanent teeth, 42 complete deciduous teeth, and 11 postcranial elements. These specimens are considered to represent at least 35 individuals and are based on material recovered up to 1989 (Alpagut et al., 1990). The number of specimens has increased since then, but these lists remain unpublished at present. Two species of hominoid are probably represented at Paşalar based on both metrical (upper M1) and morphological variation in the canines and incisors (Alpagut et al., 1990). Ninety percent of the hominoid sample is represented by one species—*Griphopithecus alpani*—and the remaining 10% has not yet been given a species name but has been assigned to *Griphopithecus sp.* (Alpagut et al., 1990).

During initial SEM (scanning electron microscope) examination of Miocene hominoid (*Griphopithecus alpani*) specimens from Paşalar, Turkey, for the purposes of dietary reconstruction (King et al. 1994, 1999; King, 1997), features were found on some of the specimens which differed from the microwear associated with diet and/or jaw movement. The possibility was considered that a taphonomic process had altered the microwear on some of the specimens.

THE PROBLEM

The occlusal phase 1 wear facet (facet 1) (Kay and Hiiemae, 1974) on specimen H272 (Fig. 1a) from Paşalar displays a number of striations which run parallel to each other, and the surface is rough and abraded in

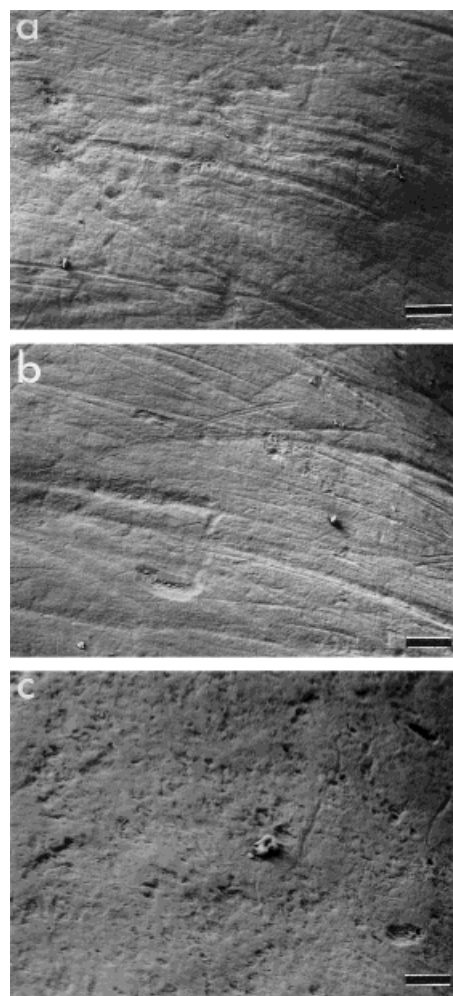


Fig. 1. Paşalar specimens suspected of having been modified by taphonomic processes. **a:** Facet 1 of specimen H272 has a rough surface texture indicative of possible abrasion by sediment. Scale bar = 50 μ m. **b:** Normal facet 1 (specimen K1367) with smooth surface texture. Scale bar = 50 μ m. **c:** Specimen K1375 may have been etched by acid. Scale bar = 20 μ m.

appearance. This is in contrast to the usual appearance of this facet, which is characterised by the presence of striations which run parallel to each other on a polished surface (specimen K1367) (Fig. 1b). It was suspected that the abrasion seen on the specimen in Figure 1a may have been the result of the postmortem processes (for example, physical abrasion by sediment) rather than caused by diet during life.

On another specimen from Paşalar (K1375) (Fig. 1c), a number of round pits can be seen on the surface which are arranged in a uniform manner. These pits are part of the enamel structure (enamel prisms), and the enamel appears to have been etched by acid, thereby exposing the enamel prisms. It is necessary to know whether the apparent acid etching had occurred during the animal's life (i.e., through the ingestion of acidic fruits) or as a result of postmortem exposure to an acidic environment.

MATERIALS AND METHODS

Six human lower molar teeth (with the roots still attached) from the late Neolithic cave burial site of Burmegnez in southeast Malta (for details of this site see Keith, 1924) were used for three taphonomic experiments. These were isolated, uncatalogued teeth which are housed at The Natural History Museum, London. The specimens were first cleaned following the methods of Gordon (1980, 1982) in order to remove any dirt that might have obscured microscopic damage. This entailed gently brushing the teeth with water and detergent using a sable paintbrush, and then applying a 50% solution of household bleach to lift any organic matter, followed by a final rinsing with water.

The occlusal surfaces of the teeth were examined using an ISI ABT-55 scanning electron microscope (SEM) in WET SEM mode. This type of SEM is useful for the examination of original specimens, as there is no need for a conductive coating to be applied to the sample or for it to be permanently mounted on a stub. The WET SEM works in the following way. While the electron gun and column are maintained at a high vacuum (10^{-4} torr), the specimen chamber is held at a lower vacuum (10^{-1} – 10^{-2} torr) (Taylor, 1986). High energy back-scattered electrons (BSEs) are used to image the specimen as the increased "noise" (air) in the chamber resulting from the lower vacuum interferes with the signal. The ISI ABT-55 SEM is fitted with a Robinson's back-scattered electron detector which is a wide-angled scintillator-photomultiplier. This type of detector increases the signal emitted by the specimen by amplifying the number of electrons collected by the detector

(Bozzola and Russell, 1992). The air molecules present in the chamber help to dissipate any electrical charge which may build up on the specimen, which means that specimens do not need to be coated with a conductor. This has been a very beneficial development in terms of examining valuable fossil material (for full discussion of this SEM system and its use in the examination of fossil material see Taylor, 1986). Most previous microwear research has been carried out using secondary electron (SE) imaging for which specimens require the application of a conductive coating. Examination of specimens has revealed that BSEs produce better images in terms of contrast, clarity, and depth of field (King et al., 1994; King, 1997). BSEs also produce images which are more representative of what is seen under a light microscope; that is, they are closer to reality (Taylor, 1986). Ungar (1994) has also noted the advantages of BSE imaging with regard to dental microwear analysis. Depending on the type of conventional SE SEM used, differences between BSE and SE SEM techniques could result in variations both in the appearance of dental microwear features made during an animal's life and microscopic alterations caused by experimental abrasion/erosion.

Before each experiment, the specimens were examined in the SEM to provide a record of the unaltered microscopic wear. Specimens were oriented so that the mesial edge of the occlusal surface was aligned at the top of the viewing screen of the SEM, and magnification, which ranged from $\times 7$ to $\times 200$, varied from specimen to specimen but was always standardised for each individual tooth. This range of magnification was used so a general picture of the modification of larger areas of the enamel surface could be seen as well as details of smaller patches of the enamel. Working distance also varied according to specimen but was always consistent for each tooth examined. An area on the hypoconid was examined for each specimen because it would be readily identifiable as the experiments progressed.

Acid erosion

Hydrochloric acid. One specimen was placed in a 2.5% solution of hydrochloric

acid (HCL) (pH 0.66) in order to simulate the effects of digestion by a predator. The tooth was left for 30 min and was then examined using a light microscope to check for any gross damage that might have occurred. No alteration was apparent, and the specimen was then placed in the acid for another hour and checked again. It was then immersed in the acid for a further hour, rinsed with water, and examined in the SEM. The total time of immersion in the acid was 2 h and 30 min.

Citric acid. A second experiment was conducted using acidic fruit. This was to simulate acidic etching which may have occurred during chewing in the mouth in addition to that which might have taken place during digestion by a predator. A specimen was placed in concentrated citric acid (lemon juice, pH 2.16) to simulate the effects of acidic fruit on dental microwear. The tooth was left in the acid for an uninterrupted time of 46 h, after which it was rinsed in water and examined in the SEM.

It should be noted that the erosion experiments carried out in this study were testing the effect of acids on dental microwear without controlling for the level of acidity or for factors such as the buffering effect of saliva.

Alkali erosion

As the deposits at Paşalar are alkaline, an experiment was carried out to investigate the effects of alkali on enamel and dental microwear. A tooth was placed for a total of 238 h in an aqueous solution of carbonate ash (with a pH of 10.54) from Oldonyo Lengai, a volcano in Tanzania. The specimen was inspected under a light microscope after 2, 4, 8, 16, 32, 64, and 128 h to identify any gross damage that might have occurred. As none was apparent, the tooth was examined in the SEM after 168 h and 238 h.

Sediment abrasion

The effects of sedimentary transport and deposition on dental microwear defects were investigated using a commercial tumbler. Three different types of sediment were used to examine the effects of different sized sands: quartz pebbles (grain diameters ranged from 2,000–11,000 μm), coarse sand

(grain size varied from 500–1,000 μm), and medium sand (grain diameters were between 250 and 500 μm). These sediment grades were obtained from screened and sorted samples of the Paşalar sediments. One tooth was placed in one of the barrels containing each of the three types of sediment. A small amount of water was added to render the sediment fluid. Each barrel was placed on a rotary tumbler which spun at 35 revolutions per minute. The circumference of the barrels was 48.5 cm, and the linear velocity was 28.3 cm/sec, or just over 1 km/h. Specimens were initially rotated for 2 h, after which they were inspected under a light microscope for any gross modifications that might have taken place. As none was apparent, the specimens were tumbled for another 2 h. As there was still no alteration apparent, the teeth were rotated for periods of time which increased on a \log_2 scale: 2, 4, 8, 16, 32, 64, 128, and 256 h. These durations were chosen so that at the beginning of the experiment short time intervals were used in order to check for rapid alteration. This gave a total number of 512 h abrasion, by which time the specimens had travelled 521 km. At the end of each abrasion session, the specimens were checked under a light microscope for any damage. In addition, they were examined in the SEM at four intervals: 16, 64, 256, and 512 h. The abrasion experiments were intended to simulate the movement of fossils in sediment or sediment which is turned over by wave action.

RESULTS

Acid erosion

Hydrochloric acid. The enamel surface of the tooth before it was immersed in the hydrochloric acid was smooth and polished with the presence of microwear features—striations and pits (Fig. 2a). After 2 h immersion in hydrochloric acid, almost all of the microwear features were removed (Fig. 2b). The acid exposed a uniform honeycomb pattern of enamel prisms over the entire wear surface. It was not possible to find the exact area on the tooth where the original SEM examination was carried out because of the obliteration of microwear features and the alteration of the enamel surface.

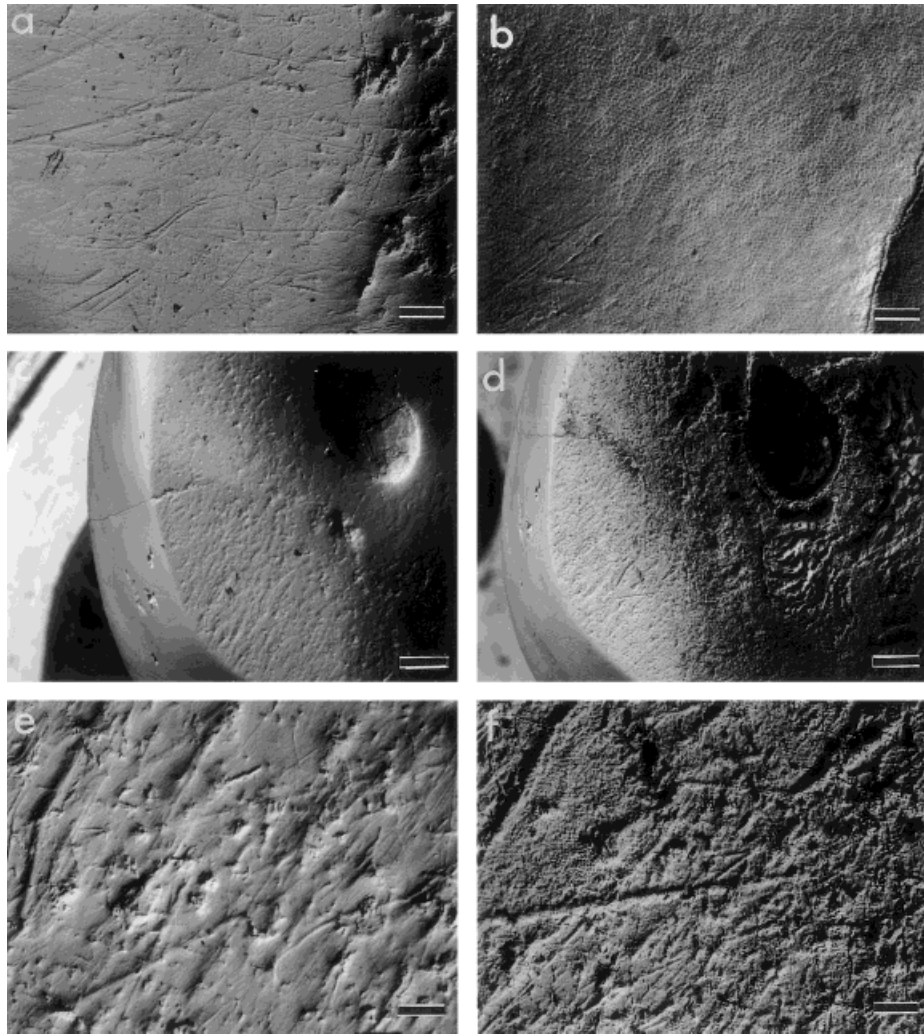


Fig. 2. The effect of acid on dental microwear. **a:** Tooth before immersion in hydrochloric acid. Scale bar = 143 μm . **b:** Tooth after 2 h of immersion in hydrochloric acid. Scale bar = 50 μm . **c,d:** tooth before (c) and after (d) exposure to citric acid for 48 h. Scale bars = 345 μm . **e,f:** specimen before (e) and after (f) exposure to citric acid for 48 h. Scale bars = 50 μm .

Citric acid. The enamel surface of the tooth before it was placed in concentrated citric acid was polished and displayed microwear features (Fig. 2c,d). After 46 h of immersion in citric acid, damage to the enamel occurred around the area of exposed dentine and enamel prisms were exposed. Only the finer microwear features were removed by the citric acid, and the remaining defects became deeper with sharper margins (Figs. 2e,f). The alteration of the enamel by the citric acid was not so extensive as that

caused by hydrochloric acid. There was not such a uniform exposure of the enamel prisms in the specimen which was exposed to citric acid as compared to that which was immersed in hydrochloric acid, even after immersion for a much longer period of time (Fig. 2b,d,f).

Alkali erosion

The enamel surface of a tooth before it was immersed in carbonatite ash for 238 h was smooth with microwear features present

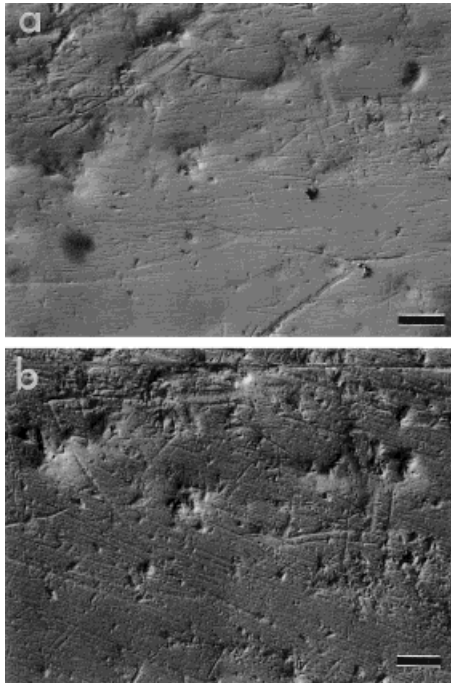


Fig. 3. The effect of alkali on dental microwear. Tooth before (a) and after (b) immersion in an aqueous solution of carbonatite ash. Orientation is slightly different in the two micrographs. Scale bars = 50 μm .

(Fig. 3a). No modification to the enamel or microwear occurred after the specimen was exposed to carbonatite ash (Fig. 3b). In fact, features can be seen more clearly than before immersion in the alkali.

Sediment abrasion

Quartz pebbles. Microwear features were present on the occlusal surface of the tooth before it was tumbled with quartz pebbles (grain size 2,000–11,000 μm) (Fig. 4a). After 64 h, the enamel had been lightly polished, and some of the finer and shallower microwear features had been eroded (Fig. 4b). Further polishing occurred in the remaining tumbling sessions and is documented by SEM micrographs taken after 256 (Fig. 4c) and 512 h (Fig. 4d). The polishing and erosion that occurred in this experiment were not extreme. Only the finer features that had little depth to them were removed, giving the enamel a smoother appearance on some areas of the enamel surface.

Coarse sand. No modification to the enamel occurred on the specimen that was tumbled in coarse sand (grain size 500–1,000 μm). Before the experiment, the tooth exhibited microwear features over the entire enamel surface (Fig. 5a). At no stage during the experiment, even after 512 h of abrasion by the coarse sand, was there any obliteration of the microwear (Fig. 5b–e).

Medium sand. The most noticeable alteration to the teeth used for the sediment abrasion experiments occurred when the specimen was tumbled with medium sand (grain size 250 with 500 μm). Microwear features were present on the surface of the tooth before the experiment began, with dentine exposed on the cusp tip (Fig. 6a). After 16 h of abrasion, a large area of damaged enamel resembling a pit appeared below the exposed dentine (Fig. 6b). No other modification occurred. The damaged area was slightly larger after 64 h (Fig. 6c), and after 256 h (Fig. 6d) it had further enlarged, as had the damage just below the dentine exposure. The most dramatic change occurred after 512 h (Fig. 6e), with extensive pitting all over the buccal face of the cusp (i.e., the left half—from top to bottom—of the micrograph). The pits were small, with the majority being smaller than 5 μm . The texture of the enamel was rough and lacked any polishing at all. This contrasts with the effect of mastication, which usually produces some polishing of the enamel. Most microwear features were obliterated, and the few remaining in this area were eroded (Fig. 6f). The damaged area was approximately five times bigger than it was after 256 h of abrasion (see Fig. 6d) and had coalesced with the exposed dentine (Fig. 6g).

Heavy pitting caused by abrasion is evident on the buccal portion of the cusp, and it can also be seen inside the damaged area. However, the lingual face of the cusp, towards the centre of the occlusal surface of the tooth (i.e., to the right of the micrograph), remained unaltered, and microwear features can still be seen here. The same pattern of heavy pitting caused by abrasion on the outer areas of the occlusal surface but not towards the centre of the tooth was seen also on each of the cusps (protoconid, hypoco-

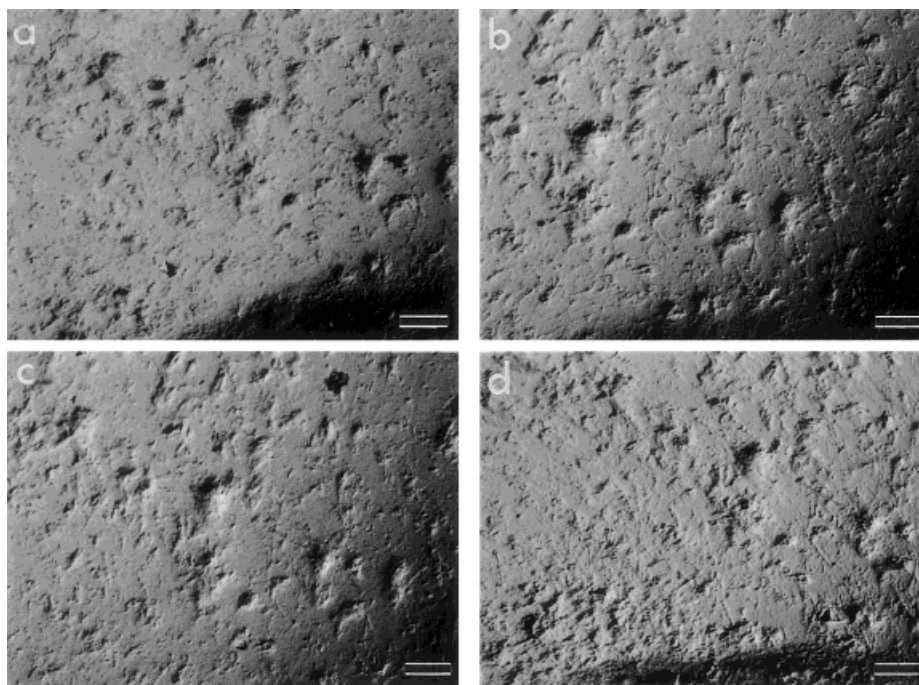


Fig. 4. The effect of abrasion by quartz pebbles on dental microwear. Specimen before (a) and after 64 (b), 256 h (c) and 512 h (d) of abrasion. Scale bars = 50 μ m.

nulid, metaconid and entoconid). One possible explanation for this is that the long axis of the tooth affected the way the tooth rotated in the sediment and so controlled the distribution of abrasion. The roots of the tooth were intact on the specimen used in this experiment, and the long axis of the specimen ran from the top of the crown to the base of the roots, so it is possible that the tooth rotated around the long axis, with maximum damage occurring around the outside of the tooth.

In order to try to clarify this pattern of abrasion, we conducted a further experiment. This time an extracted human right lower molar was used, and the roots of the specimen were removed to change the long axis of the tooth to mesiodistal. The specimen was tumbled for 16 h in the same quantity of medium sand and water as for the previous experiment. This amount of abrasion time was chosen as it was after this length of time that the first SEM examination of the specimen in the first experiment took place. This allowed direct comparison of the two sets of micrographs.

Before the experiment began, microwear features could be seen on the enamel surface of the protoconid cusp (Fig. 7a,c). After 16 h abrasion in medium sand, extensive abrasive pitting could be seen (Fig. 7b,d; Table 1) with the obliteration of the microwear features. The abrasion followed the same pattern as the first experiment after 512 h; that is, there was heavy pitting on the buccal facets of the occlusal surface of the cusp but not on the lingual face.

The nonocclusal surfaces of the extracted tooth were also investigated. The mesial contact facet (Fig. 7e) both superiorly and at its centre and the buccal non-occlusal surface of the protoconid (Fig. 7f) did not display the same heavy abrasive pitting which was present on the occlusal surface.

These experiments indicate that sediment can cause abrasion of enamel. Table 1 summarises the effects of the three types of sediment on the enamel and dental microwear features after SEM examination at various intervals. The largest size particles (quartz pebbles) polished the enamel and removed some of the finer and more shallow

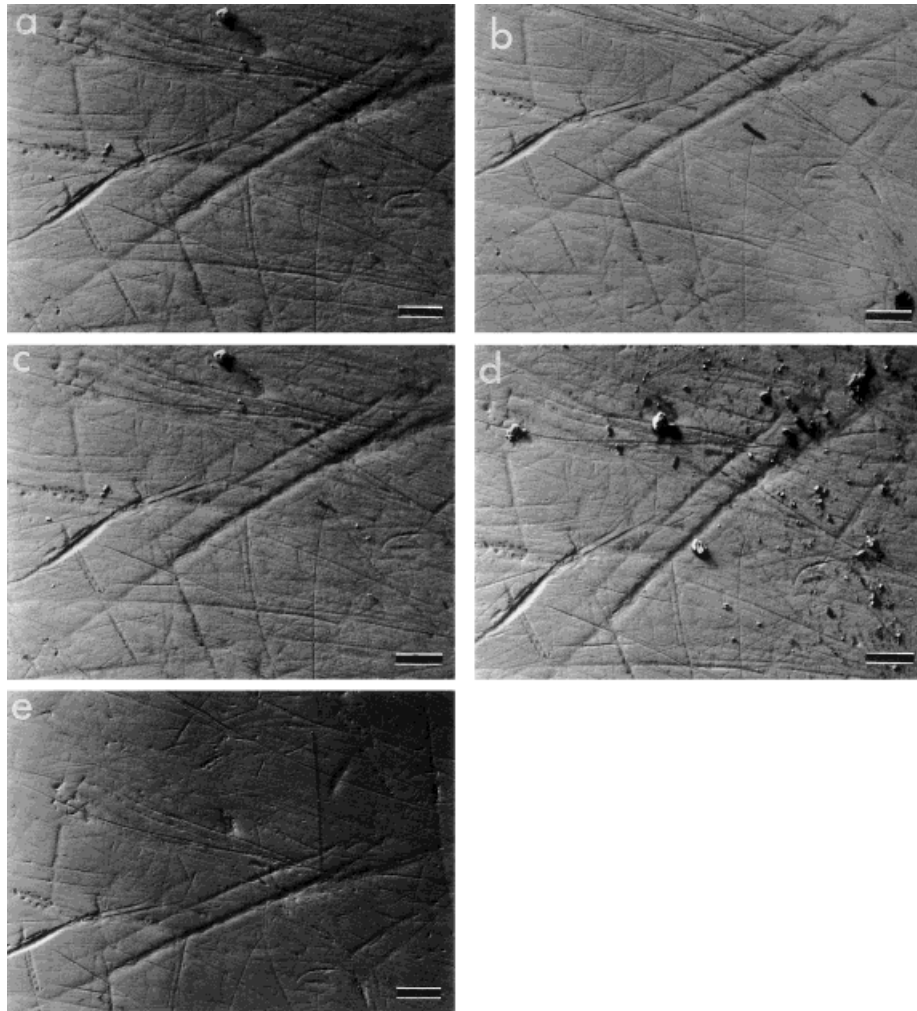


Fig. 5. The effect of abrasion by coarse sand on dental microwear. Tooth before (a) and after 16 h (b), 64 h (c), 256 h (d), and 512 h (e) of abrasion. Scale bars = 50 μ m.

features. No alteration to the enamel or microwear features occurred when a specimen was abraded with coarse sand. The smallest particles used in this study—medium sand—caused the most damage to the microwear features and enamel. The abrasion resulted in complete removal of microwear features, and extensive pitting was produced.

The differences in abrasion caused by the three sizes of sediment may be related to differences in the mineral composition of quartz pebbles and sand. This might explain why quartz pebbles polished and removed

only some of the finer microwear features, while the medium sand caused much more extensive removal of microwear. However, differences in the mineral composition of the sediments would not explain why only the medium sand, as opposed to the coarse sand, caused an alteration to microwear features.

Finally, a comment must be made about magnification. Most microwear studies have used magnifications for imaging specimens of between $\times 200$ and $\times 500$. In the present study, we used a maximum magnification of $\times 200$, and this may have implications for finer microwear features which can be seen

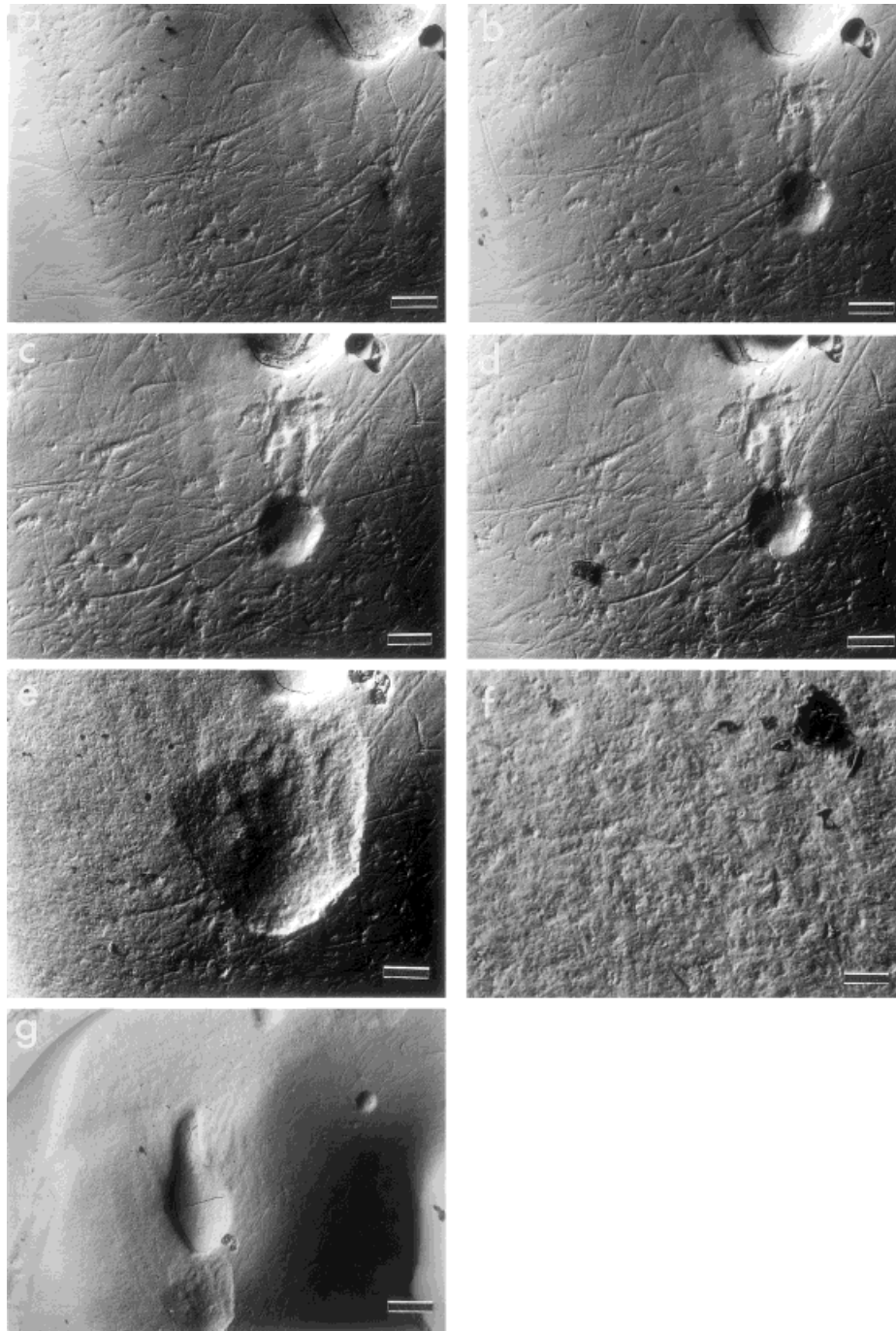


Fig. 6. The effect of abrasion by medium sand on dental microwear. Tooth before (a) and after 16 h (b), 64 h (c), 256 h (d) and 512 h (e). Scale bars = 172 μ m. f: Detail of obliteration of the microwear features. $\times 200$. Scale bar = 50 μ m. g: Coalescence of large abrasion pit with dentine exposure. Scale bar represents 556 μ m.

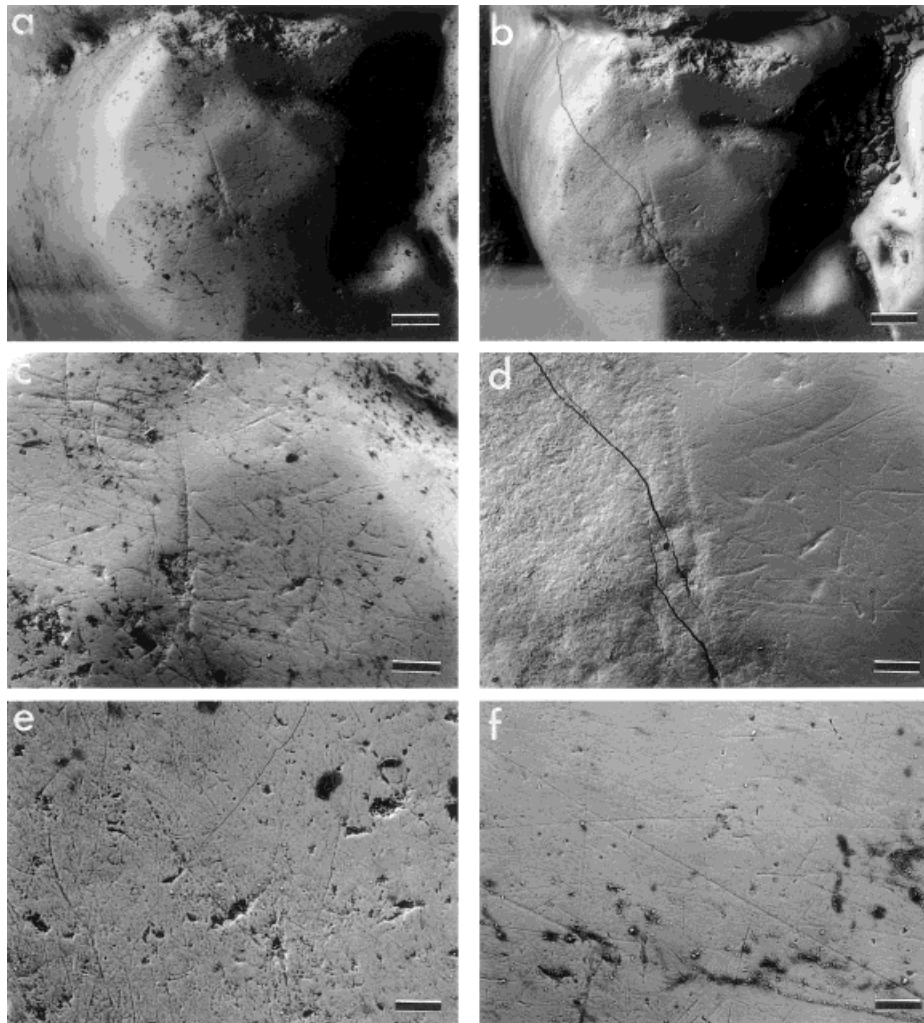


Fig. 7. The effect of medium sand on dental microwear (second experiment). **a,b:** Tooth before and after abrasion. Scale bars = 588 μm . **c,d:** Tooth before and after abrasion. Scale bars = 200 μm . **e,f:** Mesial contact facet and buccal (nonocclusal) surface of the protoconid. Scale bars = 50 μm .

only at higher magnifications. Since both the erosion and tumbling and experiments resulted in the removal of both fine and larger microwear features, it can be expected that fine microwear features seen at high magnifications would also have been removed. This may have occurred earlier on during the experiments. However, it would be expected that removal of finer microwear features would be readily detected at higher magnifications since characteristic patterns were produced by the simulated taphonomic processes. In the case of the experiments

using coarse sand where no polishing or alteration was seen at lower magnifications, it might be that removal of finer features would have been detected at higher magnifications.

Comparison with Paşalar

Table 2 lists all specimens from Paşalar examined to date which appear to have been altered by the taphonomic processes examined in this paper. One specimen from the Paşalar sample (BP1312, housed at The Natural History Museum, London) dis-

TABLE 1. *Effects of three sediment types on dental microwear*

Abrasion time	Quartz pebbles	Coarse sand	Medium sand (first experiment)	Medium sand (second experiment)
16 h	Enamel polishing and feature removal	No alteration	Appearance of pit below dentine exposure	Extensive pitting over enamel surface but not on lingual face of cusp
64 h	Enamel polishing and feature removal	No alteration	Enlargement of pit	—
256 h	Enamel polishing and feature removal	No alteration	Further enlargement of pit	—
512 h	Enamel polishing and feature removal	No alteration	Further enlargement of pit and coalescence with dentine exposure; extensive pitting over enamel surface but not on lingual face of cusp	—

TABLE 2. *List of modified specimens from Paşalar*

Specimen	Erosion agents		
	Acid	Alkali	Sediment
BP36	✓	x	x
BP61	✓	x	x
BP65	✓	x	x
BP1312	✓	x	x
F184	✓	x	x
K1375	✓	x	x
C99	x	x	✓
H272	x	x	✓

played a similar type of etching pattern to that caused by the hydrochloric acid. The top layer of enamel on the paracone cusp tip has been removed, and the network of interconnected enamel prisms has been exposed (Fig. 8a,b). The hypocone of the same specimen also displays this pattern of prism exposure (Fig. 8c,d).

Two molars from Paşalar—BP36 (housed at The Natural History Museum, London) and K1375 (housed at the University of Ankara)—display a similar pattern of enamel etching as the specimens which were immersed in citric acid (Fig. 8e,f). The finer microwear features have been removed, and there are patches of exposed enamel prisms. The features which have not been obliterated (especially specimen BP36) (Fig. 8f) are eroded and do not have accentuated margins as can be seen on the tooth which was etched with citric acid.

A similar pattern of pitting to that of the specimens which were experimentally abraded with medium-sized sand is seen in two specimens from Paşalar. Very few microwear features can be seen on specimen

C99 (housed at the University of Ankara) (Fig. 8g), and those which are present are extremely eroded. There is a general rough, pitted appearance to this specimen that is similar to modifications caused by abrasion, although the experimentally produced alteration is much heavier than that seen in the fossil tooth. It is therefore likely that tooth C99 from Paşalar has been abraded by sediment. A second specimen from Paşalar (H272) (Fig. 1a) also has a similar aspect to the specimens that have been abraded by medium-sized sand but to a much lesser extent than C99. Microwear features have not been eroded away, but the texture of the enamel appears rough and pitted and is reminiscent of the specimens that were experimentally abraded by sediment.

DISCUSSION

The purpose of the experiments reported here was to investigate the effect that various taphonomic processes can have on microscopic dental wear made during an animal's lifetime. Microscopic features that were suspected of being caused by taphonomic processes have been found on some of the fossil hominoid teeth from Paşalar, Turkey. As these marks could potentially confound any dietary reconstruction, it was important to ascertain whether they had been produced during the lifetime of the hominoids (i.e., by diet) or whether they were caused by processes which took place after death.

Effect of acids on dental microwear

The experiments conducted demonstrate that acids do affect enamel and dental mi-

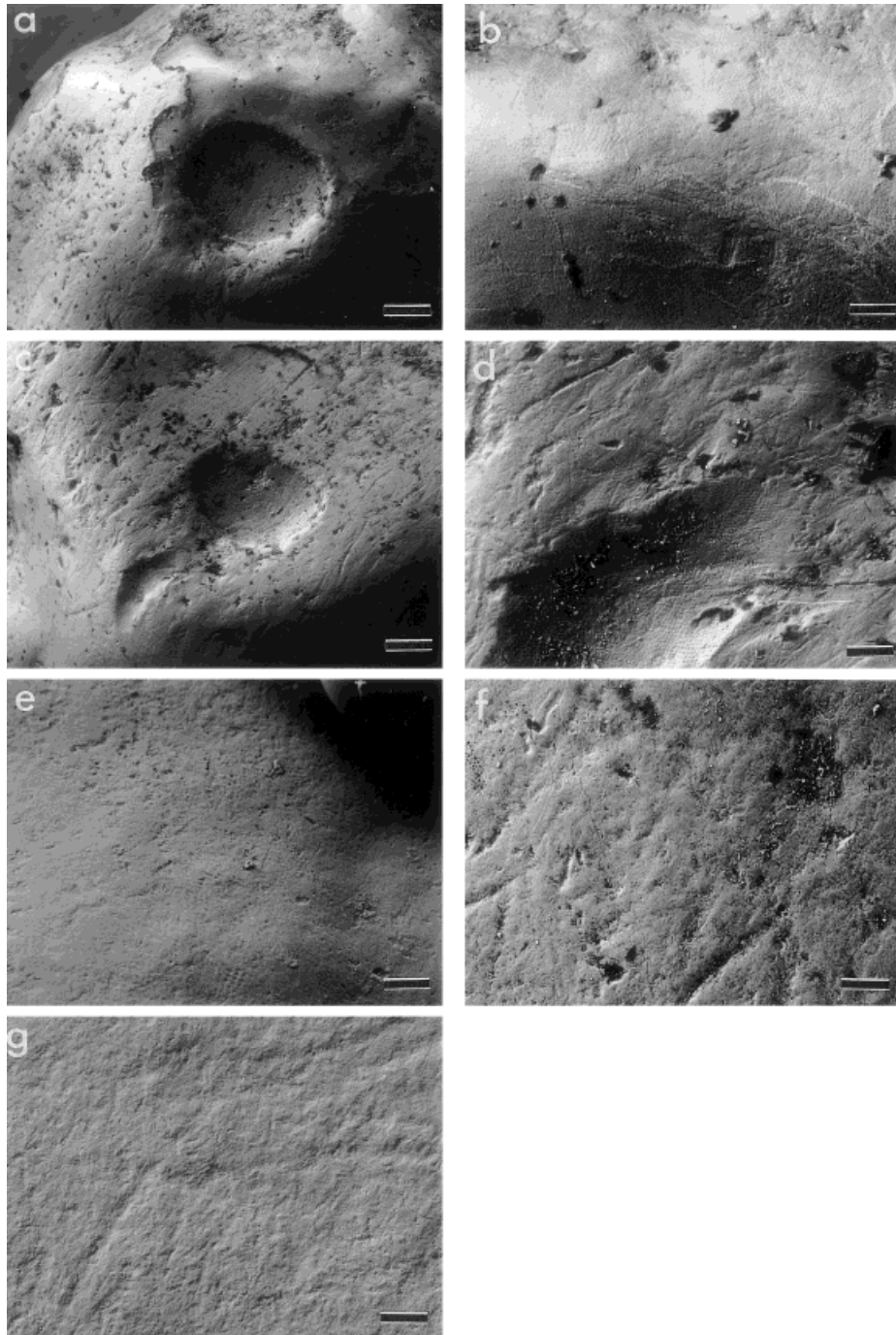


Fig. 8. Paşalar hominoid molars which have been taphonomically modified. **a,b:** Acid etching of paracone cusp tip area of specimen BP1312. **a:** Scale bar = 256 μm . **b:** Scale bar = 55.6 μm . **c,d:** Acid etching of hypocone cusp tip region of specimen BP1312. **c:** Scale

bar = 263 μm . **d:** Scale bar = 55.6 μm . **e:** Acid erosion over entire occlusal surface of specimen K1375. Scale bar = 50 μm . **f:** Acid etching of occlusal surface of specimen BP36. Scale bar = 55.6 μm . **g:** Sediment abrasion of specimen C99. Scale bar = 50 μm .

crowear by removal, in varying degrees, of the features and exposure of enamel prisms. Specimens which have been acid-etched can be readily identified and when encountered should be excluded from analyses from which inferences about past diets are made.

Hydrochloric acid caused heavy erosion of the microwear and enamel. Lighter etching resulted from immersing a specimen in citric acid. Both these types of erosion have been found in the Paşalar sample.

These two kinds of alteration can be easily identified in fossil samples. In the extreme, as with hydrochloric acid, almost all of the microwear features are removed, and the enamel is etched such that the underlying enamel prism network is exposed in a uniform manner over the whole surface of the tooth. Puech et al. (1985) also found this pattern of prism exposure when they etched a tooth with a 30% solution of phosphoric acid. With the lighter erosion, as seen in the citric acid experiment, the finer microwear features are removed, the margins of the remaining ones are sharpened, and there are localised patches of prism exposure. This pattern of removal of the more delicate microwear features has also been documented by Teaford (1994) in an experiment that investigated the effect of a 2–3 sec etching of enamel with a 30% solution of phosphoric acid.

Effect of alkali on dental microwear

No apparent alteration to the microwear features was evident from exposure to alkali. After the experiment had been carried out, however, the microwear features could be seen more clearly than prior to the experiment. It may be that the alkali had a cleaning effect on the tooth, resulting in greater clarity of microwear features. Slight differences in the orientation may also account for the variation in the appearance of microwear features before and after exposure to alkali, since it has been found that variation in specimen orientation can affect the definition of microwear features (Gordon, 1988).

Effect of Sediment on Dental Microwear

Apart from the occurrence of polishing by the quartz pebbles, only the medium-sized

sand was found to modify the microwear features within the times and degrees of abrasion used in these experiments. The enamel surface was roughened by extensive abrasion pitting, and the microwear features were completely removed. This type of abrasion has been seen in three specimens from the Paşalar.

It is not clear why abrasion should occur after different periods of time in the two experiments using medium-sized sand. The archaeological tooth was modified after 16 h, as seen by the appearance of a large pit close to the dentine exposure. However, extensive abrasion was not seen until 512 h of abrasion had taken place. Similar extensive abrasion of the extracted molar occurred after just 16 h tumbling in medium-sized sand. Why there should be such a difference in the time taken to cause the same amount of damage to these two specimens is not evident. It could be related to different enamel hardness in the two specimens or the fact that one is an archaeological specimen and the other relatively recently extracted. In any case, although further work is needed to clarify this issue, it does not alter the fact that this size of sand particles did abrade the enamel surface and that this type of abrasion can be recognised.

The experiments described above indicate that although sediment has the potential to alter dental microwear patterns, the modification is in the form of obliteration of features rather than secondary alteration of the existing microwear patterns or the formation of new features. Thus, enamel that has been abraded by sediment can be detected and the specimen excluded from further analysis. This conclusion is consistent with that of Gordon (1984), although another aspect of these results contrast with her findings. Apart from the slight polishing of enamel which resulted from tumbling a specimen with quartz pebbles, the most significant alteration to dental microwear occurred after abrasion by the smallest (medium-sized sand) sediment particles, in contrast with Gordon (1984), who found that the degree of modification to the dental microwear was positively correlated with the size of the abrasive particle. However, Gordon does not give enough detail about

the sizes of sediments she used in her experiments for any discussion of the reasons why her results contrast with those in the present study.

SUMMARY

The experiments conducted here indicate that dental microwear patterns tend to be obliterated rather than secondarily modified by taphonomic processes. These results are reassuring in that taphonomically altered dental microwear patterns can be readily identified. With the careful examination of fossil material, dietary inferences are not likely to be clouded by the effects of postmortem processes. Exposure to acids produced extensive erosion of the enamel and microwear, with lower pH producing a greater effect, and several Paşalar hominoid specimens display this type of pattern of alteration of the dental microwear. No alteration to the dental microwear occurred when a specimen was exposed to an aqueous solution of carbonatite ash. Polishing of the enamel and removal of finer dental microwear features occurred when a specimen was tumbled with the largest sediment particle size used in these experiments. No alteration to the microwear patterns was observed when a specimen was abraded with the medium-sized sediment particles. The greatest modification to dental microwear features occurred after tumbling with the smallest sediment particles where complete obliteration of microwear features was observed. Two specimens from Paşalar display this type of modification.

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LITERATURE CITED

- Alpagut B. 1990. A short history of the excavations at the Miocene site at Paşalar, Turkey. *J Hum Evol* 19:337–341.
- Alpagut B, Andrews P, Martin L. 1990. New hominoid specimens from the Middle Miocene site at Paşalar, Turkey. *J Hum Evol* 19:397–422.
- Andrews P. 1990. Palaeoecology of the Miocene fauna from Paşalar, Turkey. *J Hum Evol* 19:569–582.
- Andrews P. 1995. Time resolution of the Miocene fauna from Paşalar. *J Hum Evol* 28:343–358.
- Andrews P, Alpagut B. 1990. Description of the fossiliferous units at Paşalar, Turkey. *J Hum Evol* 19:343–361.
- Andrews P, Tobien H. 1977. New Miocene locality in Turkey with evidence on the origins of *Ramapithecus* and *Sivapithecus*. *Nature* 268:699–701.
- Alpagut B, Andrews P, & Martin L. 1990. New hominoid specimens from the Middle Miocene site at Paşalar, Turkey. *J Hum Evol* 19:397–422.
- Bozzola JJ, Russell LD. 1992. Electron microscopy. Boston: Jones and Bartlett Publishers.
- Gordon KD. 1980. Dental attrition in the chimpanzee. Ph.D. dissertation, Yale University.
- Gordon KD. 1982. A study of microwear on chimpanzee molars: implications for dental microwear analysis. *Am J Phys Anthropol* 59:195–215.
- Gordon KD. 1983. Taphonomy of dental microwear: can fossil microwear be studied productively? *Am J Phys Anthropol* 60:200.
- Gordon KD. 1984. Taphonomy of dental microwear, II. *Am J Phys Anthropol* 64:164–165.
- Gordon KD. 1988. A review of methodology and quantification in dental microwear analysis. *Scanning Microsc* 2:1139–1147.
- Kay RF, Hiiemae KM. 1974. Jaw movement and tooth use in recent and fossil primates. *Am J Phys Anthropol* 40:227–256.
- Keith A. 1924. Neanderthal man in Malta. *J Royal Anthropol Inst* 54:251–275.
- King T, Aiello LC, Andrews P. 1999. Dental microwear of *Griphopithecus alpani*. *J Hum Evol* 36:3–31.
- King TC. 1997. Dental microwear and diet in *Griphopithecus alpani*. Ph.D. dissertation, University of London.
- King TC, Aiello LC, Andrews P. 1994. Dental microwear and diet of *Griphopithecus alpani*. *Am J Phys Anthropol Suppl* 18:124.
- Puech P-F, Prone A, Roth H, Cianfarani F. 1985. Reproduction experimentale de processus d'usure des surfaces dentaires des Hominides fossiles: consequences morphoscopiques et exoscopiques avec application a l'Hominide I de Garusi. *C R Acad Sci III* 301:59–64.
- Taylor PD. 1986. Scanning electron microscopy of uncoated fossils. *Palaeontology* 29:685–690.
- Teaford MF. 1988. A review of dental microwear and diet in modern mammals. *Scanning Microsc* 2:1149–1166.
- Teaford MF. 1991. Dental microwear: What can it tell us about diet and dental function? In: Else J, Lee P, editors. *Advances in dental anthropology*. New York: Wiley-Liss Inc. 341–356.
- Teaford MF. 1994. Dental microwear and dental function. *Evol Anthropol* 3:17–30.
- Ungar PS. 1994. Incisor microwear of Sumatran anthropoid primates. *Am J Phys Anthropol* 94:339–363.